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Modelling of anelastic deformation in dual-phase steel for improved springback simulation

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Abstract

Classical elasto-plastic models assume linear elastic stress-strain relations for all stresses within the yield surface. Closer examination discloses a nonlinear relation in the elastic domain that is dependent on the prior plastic deformation. The ‘unloading strain’ can be decomposed in a linear elastic contribution and an anelastic contribution that is related to reversible dislocation movement in the crystal lattice. The anelastic contribution in the total recovered strain upon unloading is significant and therefore should be considered in accurate springback predictions.
Modelling of this phenomenon with E-modulus degradation is fundamentally incorrect and only gives a fair strain prediction after completely unloading the material. In springback situations, inner fibres of the sheet material are partly unloaded and outer fibres are even reloaded in compression. Therefore, a model is required that includes the amount of plastic pre-loading and the amount of unloading separately. For implementation of the model in a finite element code, it needs to be formulated in the complete 6-dimensional stress space and not only for uniaxial stresses. A model is presented that can be applied for arbitrary strain paths and that is consistent with the main observations in uniaxial loading-unloading-reloading experiments.

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Keywords: Springback; Anelasticity; Dislocations; Nonlinear unloading; AHSS

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1. Introduction

Unlike what is generally accepted, experimental evidence shows that assuming a Hookean behaviour to describe unloading is not realistic. It has been observed experimentally that a plastically deformed material shows a nonlinear unloading/reloading behaviour. This is caused by an extra reversible strain recovered during unloading along with the pure elastic strain. The root cause of this phenomenon is the short-range reversible movement of dislocations known as anelasticity [1-3]. The dislocation structures which are impeded by the pinning points or piled up before the grain boundaries can move to a new equilibrium upon the relaxation of the lattice stress, contributing to some extra microscopic strain. This results in the nonlinear unloading/reloading behaviour and the reduction of the effective modulus. A number of authors have claimed that the magnitude of the anelastic strain is related to the dislocation density in the material [3-6]. In a recent work, Arechabaleta et al. [6] used XRD method to quantify the dislocation density in pure iron and a low-alloy steel. The results confirmed the proportionality between the dislocation density and the anelastic strain.

From an industrial perspective, modeling of the above mentioned phenomenon is essential for an accurate springback simulation, since the magnitude of the springback is governed by the total recovered strain upon unloading of the deformed part [7]. To overcome this issue, an approach commonly referred to as the "E-modulus degradation" has been taken by various authors [8-10]. In this approach the E-modulus of the material is made a function of the equivalent plastic strain. In this way the nonlinear unloading curve is approximated by the chord modulus which is measured from the experiments. It has been shown that adopting the E-modulus degradation approach significantly improves the springback prediction accuracy by the FEM. However, It has been shown by Ghaei et al. [11] that the springback angle is over-predicted when the E-modulus degradation approach is taken.

Recently, few attempts have been made in order to model the nonlinear unloading behaviour. Eggertsen and Mattiasson [12] and Sun and Wagoner [13] have taken similar approaches based on the two-yield-surface plasticity theory and proposed two-surface constitutive models in which the inner surface defines the transition between the linear and nonlinear elasticity and the outer surface gives the yield criteria. In that way, as long as the stress state is within the inner surface, the stress-strain relation remains linear. This was found in contradiction with the experimental observations. On top of that, such models are built based on mathematical convenience rather than capturing the underlying physics of the phenomenon.

In this work by quantifying the anelastic strain, based on the physics of the phenomenon, a one dimensional model for describing the nonlinear unloading behaviour is presented. This one dimensional uniaxial model is generalized to a three dimensional constitutive model incorporating elastic, anelastic and plastic strains. The performance of the model is evaluated by comparing the predicted cyclic unloading/reloading stress-strain curves with the experimental ones.

2. Experimental

In order to determine the parameters for the anelastic model, cyclic uniaxial loading/unloading/reloading (LUR) experiments were conducted on a DP800 steel with a thickness of 1 mm. In such experiments the material was loaded to a certain force and then unloaded to zero force. In the subsequent cycles the loading force was increased by increments of 500 N. In order to determine the hardening parameters of the material, a monotonic tensile experiment was conducted. In this experiment, the specimen was strained up to 15% engineering strain. All the experiments were conducted at a constant crosshead speed of 5 mm/min resulting in a strain rate of 0.0005 s^{-1}. The experimental stress-strain curves resulting from the monotonic and LUR experiments are presented in Fig. 1.